MFI 70-117

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EFFECTS OF THE UNDERWATER ENVIRONMENT UPON WORK EFFICIENCY OF DIVERS

Contract N00014-70-C-0189

Work Unit NR 196-070

by:

Irving Streimer
D.P.W. Turner
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Sponsored by: Engineering Psychology Programs
Office of Naval Research

Man Factors, Inc.
4433 Convoy Street
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ABSTRACT

The effects of working underwater upon certain human performance characteristics during the execution of specific complex tasks were studied. The tasks examined were:

1. A complex maintenance task involving the disassembly and reassembly of a water filtration unit.

2. The execution of a mental task involving the processes of numerical reasoning, digit memory span and pattern perception.

These tasks were performed in self-paced fashion at a working depth of 33 feet. During test sessions measures were taken of breathing gas consumption rate, (Liters/min. STPD, air), as well as time and accuracy measures of the task performed. These measurements were then placed in a format which enabled comparison of dependent variable values at ground level and depths of five and thirty three feet.

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FOREWARD

This document is the final technical report of a study of human performance during the execution of complex tasks underwater. The study was conducted by Man Factors, Inc., San Diego, during the period March, 1970 through August, 1970. The work was supported by the Engineering Psychology Branch (Code 455) of the Department of the Navy, Office of Naval Research (ONR) under Contract N00014-70-C-0189. The assistance of Mr. G. Malecki of the ONR, Engineering Psychology Branch, was a constant supportive factor throughout the course of the study.

The study was conducted and written by I. Streimer, Ph.D., D. P. W. Turner, K. Volkmer and D. Guerin. The testing was conducted at the U.S.N. Pacific Missile Range, (NAS), Point Mugu, Calif.

Acknowledgement and thanks must be made to Mssrs. L. Mansfield and R. Grubel of Consolidated Film Industries whose aid enabled the calibration of the equipment employed.

INTRODUCTION

The Office of Naval Research, Engineering Psychology Branch, (Code 455) has, over the past several years, sponsored a series of research programs with the goal of developing data descriptive and predictive of diver performance characteristics and requirements during underwater work. It was immediately recognized that the success and cost-effectiveness of many undersea programs would be largely determined by human performance characteristics during the execution of those tasks requisite to assembly, construction, maintenance, control and scientific research functions. Therefore, in these particular studies, encompassing more than 500 underwater experimental tests, the primary emphasis has centered upon performance characteristics manifested during the execution of manual work tasks. To date, the experimental results garnered from these, and other programs may be summarized thusly:

1. Operator capabilities to produce maximal "breakaway" forces while in tractionless or reduced traction environments are significantly degraded.[12] These degradations vary with both the nature of the mode of force application and the nature of the biomechanical

linkages with which the force is applied. Table 1.

2. Operator ability to produce manual power is significantly degraded in underwater work performed in tractionless or reduced traction conditions. The magnitude of the degradations produced varies with the task nature, and within a given task, by the biomechanical characteristics of the man-task interactions. Thus, it has been found, that energy expended in power production via repetitive rotary efforts yields more power at less cost than do linear reciprocating manual efforts. This directional trend appears constant despite the apparently greater susceptibility of rotary effort to degradation effects produced by the reduced traction/tractionless condition.[13,15,16] Tables 2, 3.

3. Of critical importance to system designers is the finding that operators, in the performance of self-paced work, tend to maintain relatively constant levels of energy input. Differences in working efficiency occasioned by the biomechanical considerations of the man-task interaction, are compensated for by alterations in the work output level while the absolute

Table 1

Maximum Force Production Capabilities in Various Modes: Normally Tractive (Dry) vs. Tractionless (underwater) Comparisons

Rotary Mode			
Wheel Diameter (inches)	Dry Output, Mean Value (Ft. Lbs.)	Underwater Output, Mean Value (Ft. Lbs.)	Difference (Percent)
6	47.5	37.5	-21.0
12	90.0	70.0	-22.2
21	147.0	105.0	-28.6
Shaft Diameter (inches)			
2	25.0	29.0	+16.0
3	26.5	32.5	+22.7
4	26.0	32.5	+25.0

Linear Mode			
Production Mode	Dry Output, Mean Value (Pounds)	Underwater Output, Mean Value (Pounds)	Difference (Percent)
-Push-			
2 Hand	256.0	162.0	-36.7
1 Hand	206.0	106.0	-48.5
-Pull-			
2 Hand	256.0	223.6	-12.4
1 Hand	184.0	151.0	-18.0

Table 2

Self-Paced Power Output Rates For Rotary and Linear Work Modes: Normally Tractive (Dry) vs. Tractionless (Underwater)#

Rotary Work Mode	Resistance Levels (Pounds) Output: Mean Value (Hp)									
Crank Radius	Three Pounds		Five Pounds		Six Pounds		Nine Pounds		Ten Pounds	
	Dry	U.W.	Dry	U.W.	Dry	U.W.	Dry	U.W.	Dry	U.W.
6	.025	.016	*	*	.041	.029	.048	.038	*	*
9	.031	.020	.038	.027	.047	.036	.058	.045	.051	.044
12	.033	.021	*	*	.052	.036	.068	.045	*	*

Linear Work Mode	Resistance Levels (Pounds)									
	Five Pounds		Six Pounds		Nine Pounds		Ten Pounds		Twelve Pounds	
	Dry	U.W.	Dry	U.W.	Dry	U.W.	Dry	U.W.	Dry	U.W.
	.025	.025	.019	.016	.024	.020	.043	.042	.027	.022

*Data not obtained.   # 5 foot pool depth.

Table 3

Comparisons of Energy Costs of Repetitive Work as a Function of Task Nature, Configuration and Loading During Underwater Work[15]

Energy Cost LO_2/min/hp	Task	Radius	Resistance Level: Three Pound	Resistance Level: Six Pound	Resistance Level: Nine Pound
	Rotary Task	6	62.9	34.4	26.3
		9	48.2	29.3	24.8
		12	49.2	28.9	25.2
			Resistance Level: Six Pound	**Resistance Level: Nine Pound**	**Resistance Level: Twelve Pound**
	Flexion Extension Task	N.A.	65.7	53.6	48.9

levels of energy input remain relatively constant. Referral to Tables 4, 5,[13,16] reveals that energy input levels, as determined by breathing gas consumption rates and absolute values of oxygen uptake are virtually identical across two tasks despite significant differences in the task natures and work output levels.

4. In consonance with the findings expressed in the preceding paragraph, it has been observed that operators performing self-paced tasks tend to restrict their energy input levels to rates which maintain them in an aerobic or oxygen debt-free condition. Further analyses of the data reveals constant relationships between work output rates and oxygen uptake rates.[13,17] Tables 4, 5.

5. Previously obtained data reveals constant relationships between energy input levels, measured as Liters oxygen/min., heart rate and productivity level.[13-17] These relationships are similar to those found in traditional ergonomic studies of normally tractive performance in normal environment[1,4,7-10] and clearly indicate the applicability of certain ergonomic methodological approaches to the evaluation of operational

Table 4

Performance Characteristics as a Function of Depth, Rotary Task

Dependent Variable	Ref. #13 Normal Traction	Ref. #15 5 ft.* Depth	Ref. #16 33 Ft. Depth	Ref. #16 66 ft. Depth
Uptake (LO_2/min)	1.35	1.03	1.33	1.50
Output (hp)	.051	.039	.039	.040
Output (ft/lbs/min)	1683.0	1287.0	1287.0	1320.0
Work Energy Cost (LO_2/min/hp	26.4	27.6	34.3	38.2
Respiratory Gas Flow (Liters Air/min)	Not available		40.37	59.15
Respiratory Gas Flow (Liters Air/min STP)	Not available		20.19	19.72
Percent Oxygen Absorbed From Air	Not available		3.34	2.62

*Pure Oxygen

Table 5

Performance Characteristics as a Function of Depth, Linear Task

Dependent Variable	Ref. #13 Normal Traction	Ref. #15 5 ft.* Depth	Ref. #16 33 ft. Depth	Ref. #16 66 ft.* Depth
Uptake (LO_2/min)	1.32	1.15	1.30	1.60
Output (hp)	.026	.020	.020	.020
Output (ft lbs/min)	858.0	660.0	660.0	660.0
Work Energy Cost (LO_2/min/hp)	50.2	55.8	64.3	82.3
Respiratory Gas Flow (Liters Air/min)	Not available		39.47	61.14
Respiratory Gas Flow (Liters Air/min STP)	Not available		19.75	20.38
Percent Oxygen Absorbed from Air	Not available		3.43	2.69

*Pure Oxygen

requirements in underwater work. It should be noted that a shift has been observed in the oxygen-pulse ratio (cc's O_2/heart beat)[15-17] in the direction of an increased ratio with diver submergence, but, at a given depth, heart rate monitoring should be an effective tool in the man-rating of equipment-tool-operational requirement configurations.

6. The energy costs of work have been found to increase with increased depth.[16] This statement is derived from examination of Tables 4, and 5 which reveals that breathing gas consumption rates and liters of oxygen per unit work produced increase as a function of increased depth. It should be noted that in some of the studies[16] expired gas samples were collected after passage through the sea water and hence were subject to error produced by their differential solubility as a function of their partial pressures in accordance with Henry's Law. Nevertheless, the magnitudes of the observed differences in percent oxygen absorbed at the 33 and 66 foot depths, and the constancy of the observed values, irrespective of task nature, lead to the assumption of work energy cost differences as a function of increased depth. Further

substantiation is provided by examination of absolute oxygen uptake levels found in work at a depth of 5 feet.[17], Tables 4, 5. These values were obtained via application of closed cycle rebreather systems and were not susceptible to differential solubility effects attributable to partial pressure differences at various depths.

7. Increased performance degradations, manifested as increases in total energy costs and task accomplishment times, have been found to accompany increased task complexity.[14,17], Table 6. The data, derived from studies of operator performance in a complex maintanance task at a pool depth of 5 feet, has yielded performance degradations capable of altering various concepts of system design stemming from expectations of human performance. The possible impact of these changes upon system design has been discussed in the literature.[18,19]

In view of the significant degradations found during the performance of complex tasks under relatively ideal underwater conditions an experimental program has been executed, under ONR Contract N00014-70-C-0189, whose goals were the following

Table 6

Land Versus Water Comparisons of Time and Heart Rate for the Maintenance Task[14,17]

	Heart Rate (BPM)	Heart Rate (BPM)	Heart Rate (BPM)		
	Land	Water	Difference	Percent Difference	"t" Value
Heart Rate (BPM)	106.4	113.9	7.5	7.04	4.5 $<$ .01
	Time (Seconds)	Time (Seconds)	Time (Seconds)		
Time (Seconds	359.0	588.5	229.5	63.92	17.3 $<$ .01

determinations:

1. The effects of a 33 foot working depth upon the rate at which a complex maintenance task is executed.
2. The effects of a 33 foot working depth upon the absolute value of breathing gas consumption.

The above goals are continuous with previous efforts and were expected to yield data which would allow the development of curves descriptive of certain performance aspects at depths of 5, 33 and 66 feet.

In the course of our previous study efforts it became apparent, that despite the relative rapidity with which learning plateaus were achieved in dry land training, the development of learning plateaus underwater took an inordinately long time. Figs. 1, 2. We were intrigued by considerations stemming from questions about the effectiveness of mental processes underwater. Previous studies had shown that some type of degradation could be expected and we therefore included a subtask which was primarily mental in scope. The task, described in Appendix A, required operators to engage in numerical reasoning, digit memory span and pattern perception processes.

We examined, as a function of the 33 foot depth, such dependent variables as the number of problems correctly solved and the number and type of errors generated. In consonance

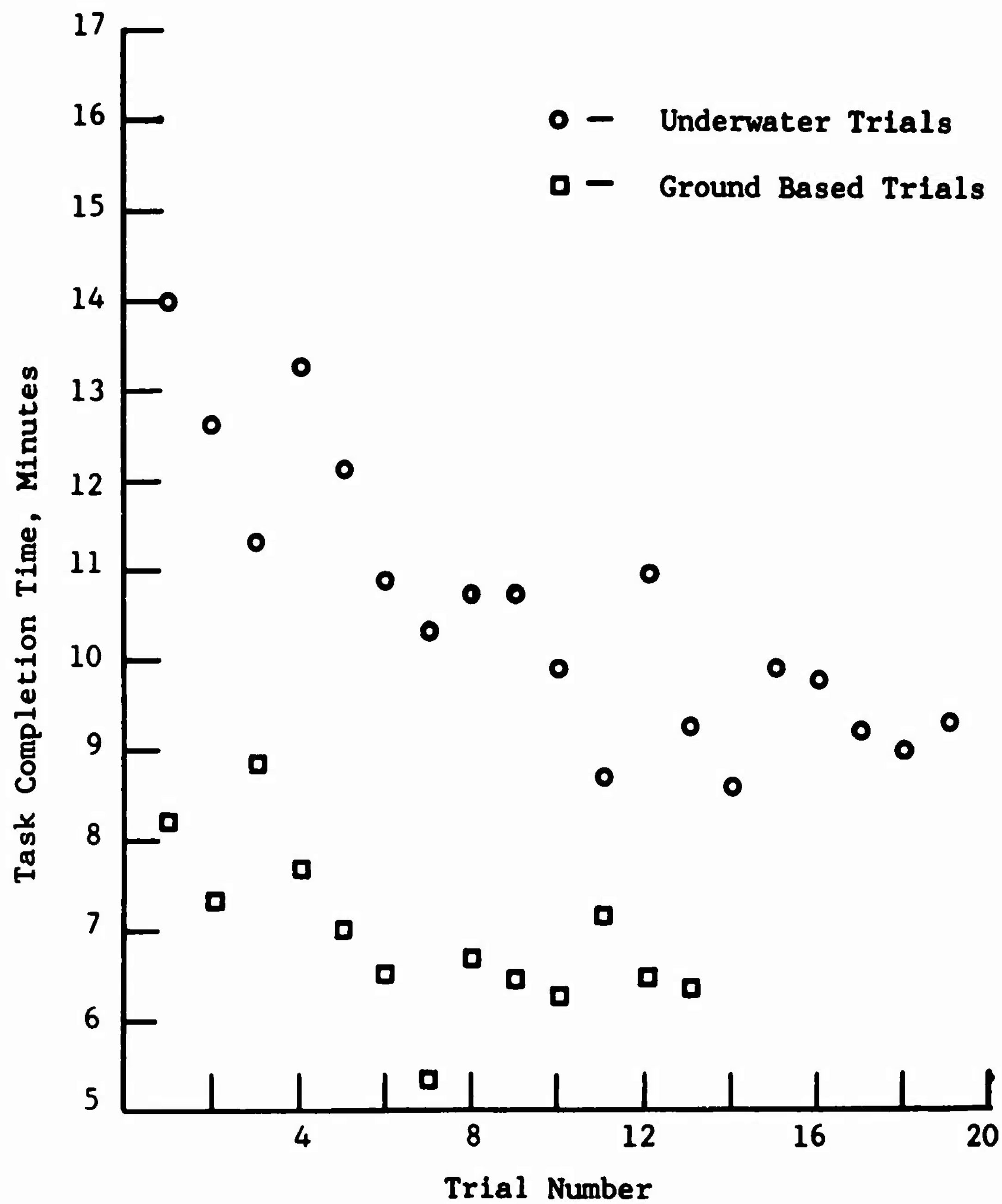

Figure 1. Maintenance Task Learning Curve, Subject 1.

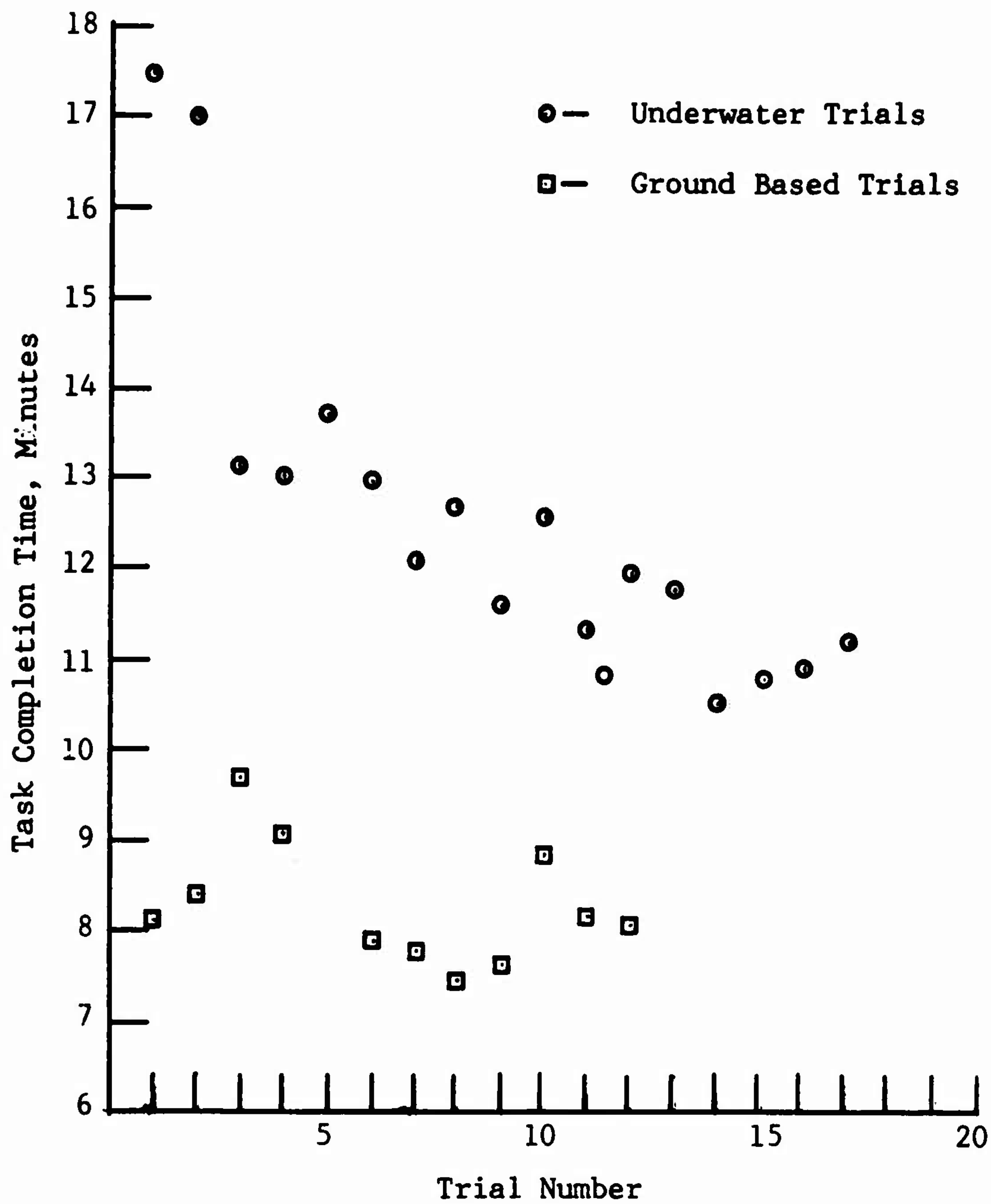

Figure 2. Maintenance Task Learning Curve, Subject 2.

with the overall experimental approach we sought to determine:

3. The effects of the 33 foot depth upon the absolute value of breathing gas consumption during a primarily mental task.

4. The effects of duration of exposure to the 33 foot depth, as determined by the presentation order of the task sequence, upon the performance characteristics measured in both tasks.

PROCEDURES

Two subjects, 27 and 32 years of age were employed as divers. The subjects were certified Los Angeles County SCUBA divers and, at the initiation of the test program, had each accumulated a minimum total of over 500 experimental dives via participation in previous programs.

In satisfaction of the experimental design, subjects were required to perform the required tasks in a self-paced mode. The tasks may be described as follows:

1. Maintenance

Subjects were required to disassemble and reassemble a Grinnel 2V2-150-A-181-11-STD water filtration unit. See Appendix A for a detailed task description and Figs. 3 and 4 for detailed diagrams of

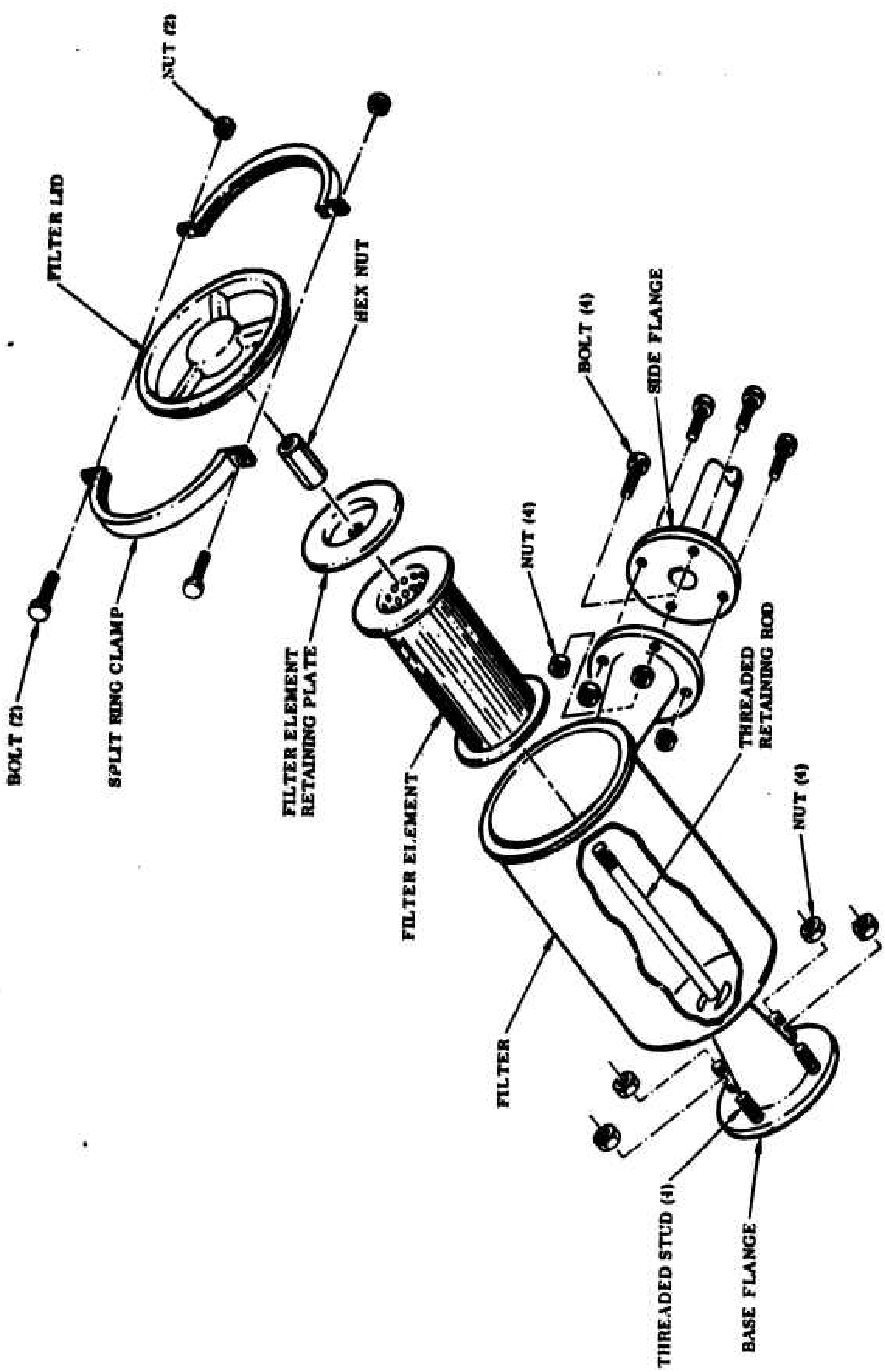

Figure 3. Maintenance Task Filter Unit (Ref. 15)

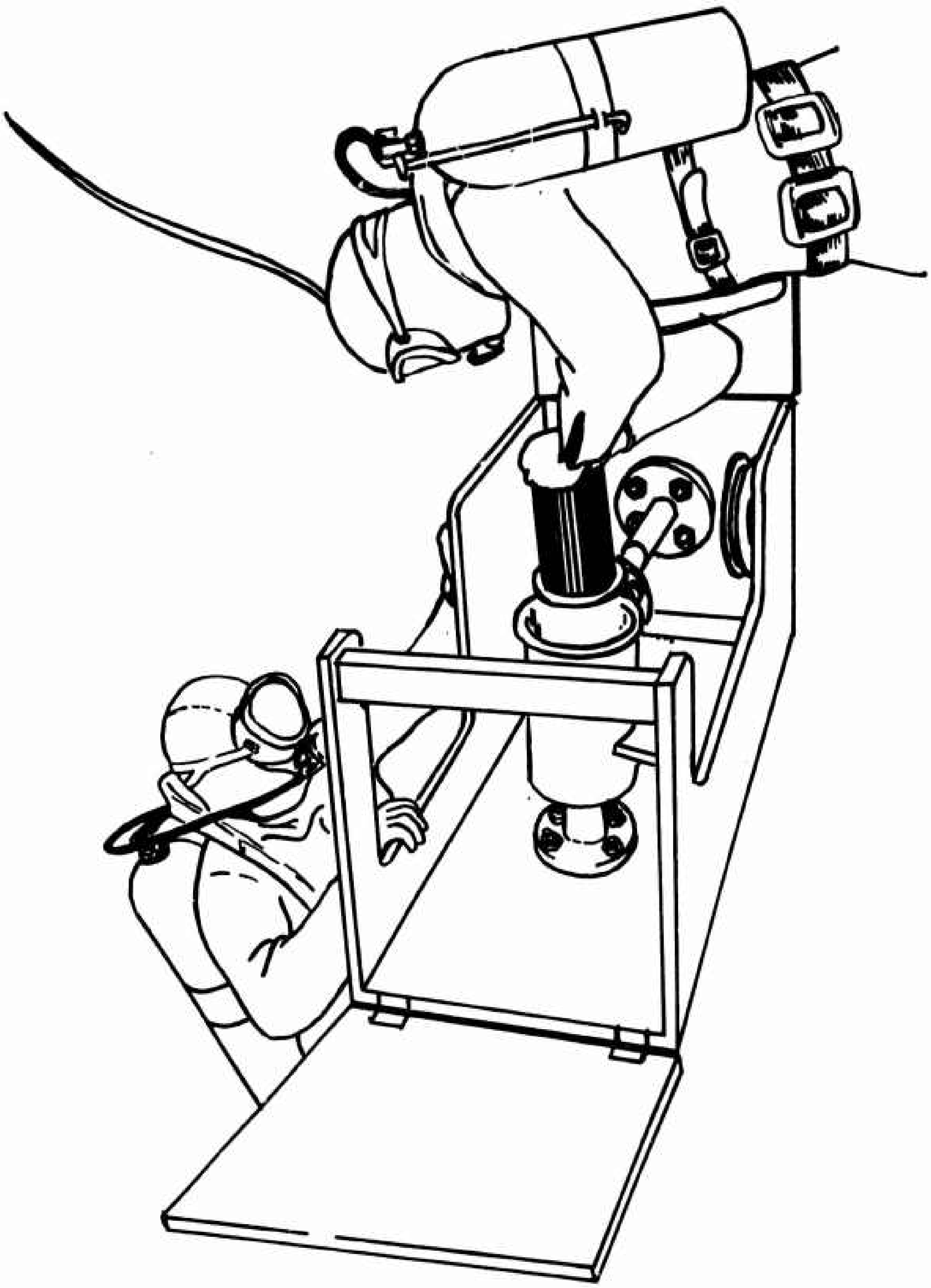

Figure 4. Maintenance Task: Divers at Work

the unit and diver work mode.

2. Mental

The task consisted of solving problems via numerical reasoning, translation of the answer via digit memory span to a keyed entry form and insertion of the keyed answer into a keyed matrix via pattern perception. See Appendix A for a detailed task description and Fig. 5 for an example of a mental task problem.

Divers descended to the 33 foot level work site. After installation of the task and an appropriate rest period, work was initiated. During all testing the operators feet were out of contact with the bottom.

As noted previously,[16] the assembly and emplacement of the support structure was in itself a task of considerable difficulty requiring coordinated diver activity. As previously stated,[16] it appears that controlled investigations of performance during multi-man complex activity would be a fruitful area of investigation.

Positions assumed at the work site were self-selected and, as found in previous studies, were similar with respect to postural attitude typically differing only in work space envelopes as a function of subject anthropometry. Subjects

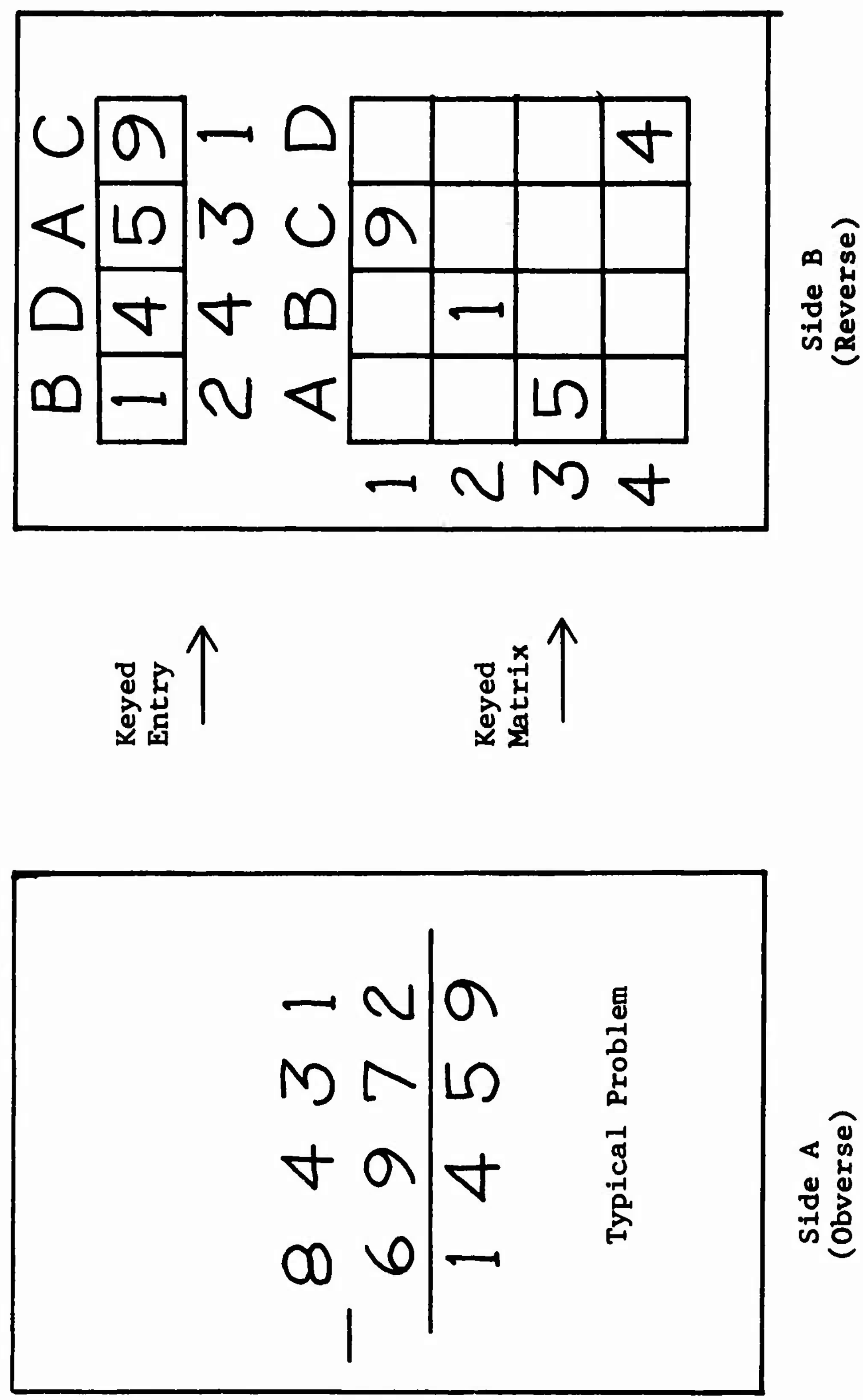

Figure 5. Mental Task Problem Illustration

executed each task 16 times, once each dive, with the tasks presented in a counterbalanced sequence. Subject entry into the water occurred at different daily times to balance possible diurnal variation effects. Subjects wore full, one-quarter inch wet suits, fins and all other appropriate underwater support equipment. During testing, test site water temperatures were monitored.

Subjects were trained on both tasks in the normal land environment and at the 33 foot depth. Training was considered accomplished when dependent variable values were obtained which were within ± 5 percent of the values obtained in the five previous training trials. The learning curves may be seen in Figs. 1, 2.

Direct measurements of breathing gas consumption rates were obtained as follows:

1. During descent to and ascent from the work site the subject diver used the self-transported SCUBA bottle. At the signal to commence the test the subject diver switched over to one of two "work" SCUBA tanks present at the work site. Upon completion of the first task the subject switched to the second "work" tank before starting the second task.

2. The "work" tanks had been calibrated with respect to their internal volumes by filling them with water via the employment of volumetric chemical glassware; i.e., volumetric flasks, burettes and pipettes.

3. An adapter was made which enabled connection of a volumetrically small pressure bottle to the SCUBA tank. The total volume of the small pressure bottle and adapter was 167.9 cc's. Thus SCUBA tank volumes and small pressure tank volumes were both measured to within 0.1 cc.

4. After connection of the small pressure tank to a large SCUBA tank, the pressure and temperatures of the two vessels were equalized. The small pressure bottle was then weighed on a chemical balance with a sensitivity of $\pm$ 50 milligrams.

5. Subsequent to the test dive, this process was repeated. The pre and post test weight differences found in the smaller vessel were converted to the volume of air removed from the large work tank by a simple calculation:

$$\frac{\text{Pre-test-post test wt. of small bottle} \times \text{work tank vol. (Liters)}}{\text{wt. air/Liter} \times \text{Small bottle vol. (liters)} \times \text{Task time (min.)}} = \text{Liter air/min.}$$

Water tests were conducted from May 1970 through Aug. 24, 1970, at the USN Pacific Missile Range, Point Mugu, Calif. The test site was located approximately 25 yards from the end of a pier. Divers were transported from the pier to the test site marker buoy by boat. During this time test site temperatures fell within the range of 51 to 62°F with a mean value of 54.7°F.

RESULTS

Treatment of the Data

Data were subjected to post-hoc comparisons using the Sheffeé method to test for significance. This procedure was applied for the following reasons:

1. In some cases, comparisons of interest exceeded the J-1 orthogonal comparisons which could be made. Since the questions asked of the data could not be considered as independent of each other, a conservative analysis was required.
2. In those cases when dependent comparisons could be made in terms of the questions posed, the requirements for orthogonality could not be met because of unequal sample sizes.

The Sheffeé post-hoc comparisons may be interpreted as follows: If we consider all possible comparisons (Ψ_g)

which can be carried out on the J means, the probability is .95 that the confidence interval statements are true <u>simultaneously</u> for all comparisons (ψ_g). That is, the chances are 95 to 100 that every one of the 95 percent confidence levels calculated for each comparison contains the true value for that comparison.[6]

Table 7

Shaffeé 95% Confidence Intervals

ψ_1*	Gas as function of task	$0.75 \leq \psi_1 < 7.90$
ψ_2	Gas as function of order across tasks	$-2.10 < \psi_2 < 5.05$
ψ_3	Gas as function of order (Maintenance)	$-1.814 < \psi_3 \leq 8.294$
ψ_4	Time as function for order (Maintenance)	$-1.503 \leq \psi_4 \leq 0.543$
ψ_5*	Time as function of environment (Maintenance)	$1.905 \leq \psi_5 \leq 4.003$
ψ_6*	Productivity as function of environment (Mental)	$-11.051 \leq \psi_6 \leq 5.373$
ψ_7	Productivity as function of order (Mental)	$-4.647 \leq \psi_7 \leq 0.897$
ψ_8	Error as function of environment (Mental)	$-0.504 \leq \psi_8 \leq 2.154$
ψ_9	Error as function of order (Mental)	$-2.170 \leq \psi_9 \leq 0.422$

*Any confidence interval for a comparison (ψ_g) that excludes zero is considered to be significant at the .05 level.

DISCUSSION & RESULTS

The study revealed that certain aspects of human performance important to system design are significantly degraded as a function of the underwater environment. These degradations were manifested as a significant increase in the time required to perform a complex maintenance task and a significant decrease in the rate at which certain mental processes were executed.

Other key findings, obtained by comparison of this study's results with previous study results, show that respiratory flow volumes are greater as a function of depth and, substantiative of previous findings, the absolute level of human self-paced effort during the performance of complex work is greater than that found in simple repetitive work. Similarly it was found, as might be expected, that breathing gas consumption rates are greater during the performance of maintenance type activities than during the performance of mental tasks alone. Table 8, Fig. 6.

Of critical importance to design engineers are those considerations stemming from the increase in maintenance task accomplishment times. Increases in task accomplishment times, or, stated, conversely, reductions in productivity per unit time must be compensated for via the provision of more men or

Table 8

Summary Table of Significant Dependent Variables: Descriptive Data, Underwater.

		Maintenance			Mental		
		S_1	S_2	Total	S_1	S_2	Total
L/Air/Min.	$(\bar{X})$	40.26	42.04	41.15	35.37	38.32	36.79
	S.D.	4.15	4.31	8.39	5.34	5.13	10.28
	I1S.D.*	73%	73%		50%	75%	
Time (min)	$(\bar{X})$	9.14	11.09	10.11	Not Applicable		
	S.D.	0.67	0.58	1.16			
	I1S.D.*	63%	75%				
Productivity (# of problems completed)	$(\bar{X})$				25.06	22.31	23.68
	S.D.				3.11	2.15	2.97
	I1S.D.*				75%	81%	

*Trial percentage encompassed by plus or minus one S.D. of the mean.

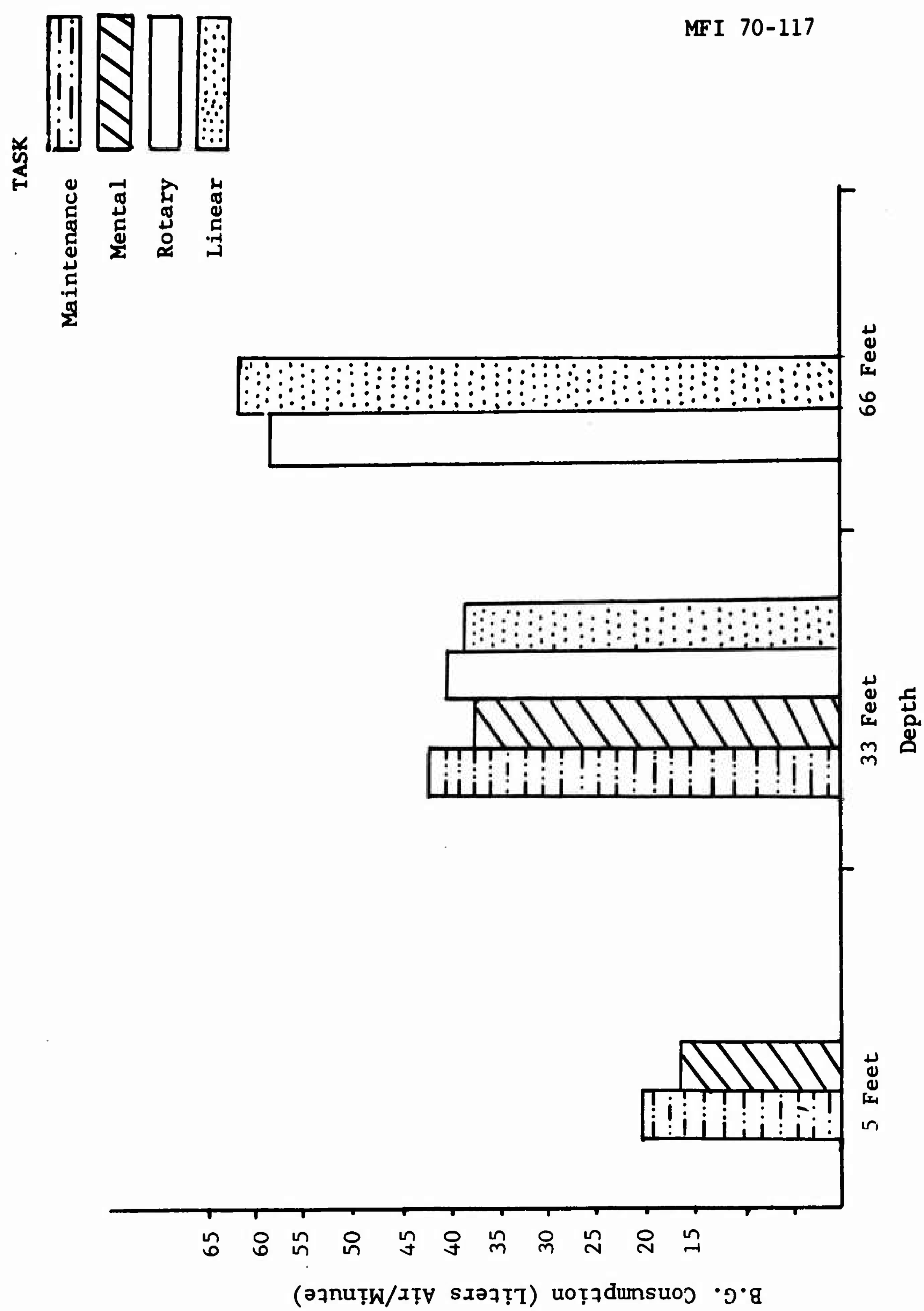

Figure 6. Breathing Gas Consumption Rate, as a Function of Water Depth

time (man-hours) or conversely, via the incorporation of design features which will result in job simplification. Since the last alternative is not always feasible the net result may be the provision of more life support expendables and/or the alteration of all mission activity scheduling as a function of slippages in the programming occasioned by the reduced operator productivity. The net consequence is an increase in overall system cost.

The significant differences in task accomplishment times between "dry" and "wet" conditions are of course important to designers and, hopefully, in conjunction with other data may serve to provide a basis from which "dry" study data may be extrapolated to actual undersea problems. What is perhaps more indicative of the nature of the problem is that a comparison of the accomplishment times found in a previous study at a five foot depth with our present study values reveals mean values of 9.8 and 10.1 minutes, Tables 6, 8 respectively. This seemingly small difference contains a further element of difference; specifically, one step in the previous study's maintenance protocol was eliminated in this study with a consequent time saving of approximately 0.25 minutes. Consequently, the obtained difference is 0.55 minutes, an increase of approximately

5.5 percent. It is this increase in time, coupled with the observed increase in respiratory flow rates, which poses a significant problem to system designers. In a previous study,[16] the constancy of respiratory flow volumes during the performance of self-paced manual work was noted. At a working depth of 33 feet, irrespective of the task nature, respiratory flow volume rates averaged 39.9 liters/min. (STP).[16] In this study the maintenance task performed at 33 feet revealed a gas flow rate of 41.15 L/min. (STP), Table 8, an increase of 3.4 percent. It should be noted, that in a study conducted in a pool using a closed cycle rebreather system, the absolute level of energy uptake (Liters oxygen/min.) was higher during the performance of self-paced maintenance activity than during the performance of repetitive manual work.[17] An oxygen uptake rate mean value of 1.05 LO_2/min. was found during the performance of self-paced repetitive work, irrespective of task nature or resistance levels.[13] A corresponding oxygen uptake rate of 1.42 LO_2/min. was found during the performance of a maintenance task essentially identical to that in this study.[17] These energy costs must now be further scrutinized in the light of the findings from still another study.

A recently completed study[16] examined the energy costs of

manual work underwater as a function of working depth. The methodologies employed involved the collection of effluent SCUBA regulator gases after passage through water. Such a technique is subject to errors produced by the differential solubilities of the oxygen and carbon dioxide as a function of their partial pressures in accordance with Henry's Law. The solubility of carbon dioxide is significantly greater than that of oxygen and it had been indicated[5] that the obtained oxygen values may be suspect because respiratory quotients were not established. Specifically, the oxygen uptake values were derived by multiplying the respiratory flow volumes by the percentage change in oxygen found in the respired gas. Thus, if the respiratory quotient was to change, subjects could use more oxygen without our cognizance, an obvious measurement error.

Despite this apparent weakness in the methodology employed in a previous study, we believe that the following facts make possible the extrapolation and comparison of these present data with previously obtained data in a meaningful manner. Over the past several years linear relationships between heart rate, oxygen uptake, work output rates and task accomplishment times have been established via experimentation employing closed cycle rebreather systems.[13-15] Similarly, relationships have been established for work output rates, heart rates, respiratory

flow rates and task accomplishment times in studies employing SCUBA apparatus.[16] It seems permissable to state that, in view of the observed constancy of these relationships and the extremely narrow ranges of input (respiratory flow rate and/or oxygen uptake) and output (horsepower and/or task accomplishment time) subjects maintain relatively constant respiratory quotients. It seems highly improbable that the factors of respiratory flow volume rates, work output levels, task accomplishment times, oxygen pulse ratios and absolute volumes of oxygen uptake would remain almost constant over hundreds of experimental trials while the Respiratory Quotient was subject to major fluctuations. Thus, aside from the error introduced via the solubility of oxygen in water we may consider the previously obtained oxygen uptake levels as good approximations of the absolute uptake levels. If this premise is continued, then the respiratory flow rates found in this study, when multiplied by the percent of oxygen absorbed at 33 foot depths found in a previous study yields an oxygen uptake level of 1.38 LO_2/min. If maintenance task flow rates found in this study are compared directly with repetitive task flow rates found in a previous study,[16] a difference of 3.5 percent is observed which should yield an uptake level of 1.37 LO_2/min. This value, slightly

higher than that found in repetitive work, is still within the range of values found previously in both SCUBA and closed cycle rebreather system studies.

To the design engineer, the important factors are those derived from considerations of the narrowness of the range of input level by the two subjects and the extension of the task accomplishment times. Each diver manifested great performance constancy, the standard deviations for respiratory flow rates and task accomplishment times were never more than 10.3 and 7.3 percent of the mean values, respectively for each diver and one standard deviation was typically found to encompass 73-75 percent of the trial runs. Table 8. Similarly, in previous studies one standard deviation was found to typically encompass 75-80 percent of the trial runs.[17] A factor of significance in the interpretation of the results is that the presentation order did not have significant effects on the maintenance task accomplishment times, mental task productivity or respiratory flow volume rates. The inference is that the divers worked at rates which were comfortable for them and, in the exposure time of this study, did not suffer sufficient fatigue to change performance characteristics. Thus, it may be assumed that divers will work at relatively constant output rates which are

determined by the interaction of their self-selected energy input rates and the biomechanical efficiency of the task. During task performance innate differences in the task efficiency will result in compensatory output rate alterations, a finding substantiated by our previous studies wherein alterations in the nature and efficiency of the task were found to produce output alterations while input levels were held relatively constant.

Reference to Table 8, Fig. 6 reveals that breathing gas consumption rates for manual work are held within extremely narrow ranges. To illustrate, within the scope of this study, we performed 12 additional trials at a depth of 5 feet. At this depth the maintenance task required a mean flow rate of 20.93 L/air/min., at 33 feet 41.14 L/air/min. Table 8, Fig. 6. These values may be contrasted with those obtained from repetitive manual work at 33 and 66 feet which were 39.92 and 60.15 L/air/min., respectively. Fig. 6. It thus appears that the values found in the present study are consonant with the values previously obtained in studies of repetitive manual work underwater.

Significant differences were found in gas consumption rates between mental and maintenance tasks, a not unexpected finding. Table 8. The differences are primarily attributable

to the reduced activity of the man and are seen to be approximately a 10.5 percent reduction in magnitude. Table 8.

The last item of significance stems from the consideration of mental process productivity in the "dry" and "wet" conditions. "Dry" subjects processed a mean value of 31.9 problems per unit time in comparison to a mean value of 23.7, a reduction of approximately 26 percent. Table 8. An artifact capable of affecting these results is that the turning of the problem "pages" underwater is accomplished with slightly more difficulty than when done on dry land. A second factor must be considered when comparing the productivity of the mental problems testing at 5 feet and 33 feet. Although the number of problems correctly done at 5 feet was slightly greater than the number done at 33 feet, 26.2 and 23.7, respectively, a mean temperature difference of almost 30°F was observed between the pool and open sea temperatures.

The implications of the study may be summarized thusly:

1. Significant degradations appear in human performance characteristics as a function of exposure to the underwater environment. These degradative alterations in output are capable of significantly changing all considerations of system design which are predicated upon assumed expectancies of human performance.

2. Humans performing self-paced work perform at rates which are remarkably constant in nature with respect to both their energy investment rates and their work output rates. With minor modifications, all the relationships established between input/output relatior-ships in normal work environments may be applied to studies of underwater work. Fig. 7.
3. The performance of complex work is more demanding than the performance of repetitive work. The disparities would seem to stem from the necessity of working in a variety of biomechanical modes with a consequent loss of efficiency as the man/object linkages vary in appropriateness. The implications seem to point the need for future research into diverse bracing systems and equipment configuration development and the evaluation of powered tools.
4. The obtained gas flow rates were consistent with those obtained in previous studies and indicate the need for the examination of complex work at increased depths.
5. The relationships found over the past several studies heart rate/oxygen uptake/breathing gas consumption

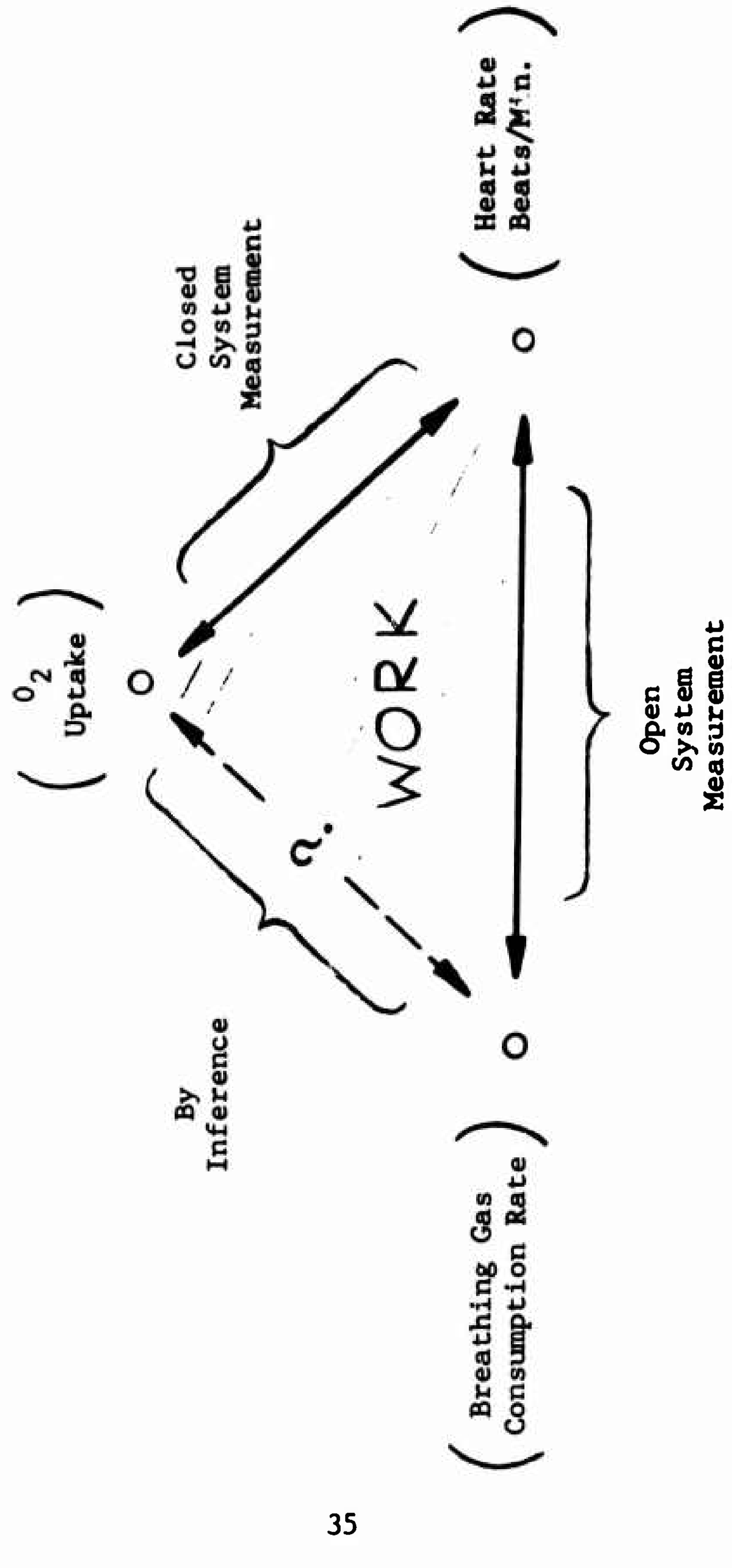

Figure 7 - Graphic Model of Work Output and Indices of Physiological Cost Relationships.

rates/productivity, Fig. 6, are sufficiently constant in nature to enable the evaluation of system components in terms of man-rating.

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APPENDIX A

Maintenance Task

The subject was confronted with a large rectangular module containing a line water filter assembly connected to water pipes by means of mounting flanges (See Figure 3). The task required the subject to unscrew nuts and open hinged module cover doors and then disassemble, reassemble filter element, remove and replace the water filter assembly and bolt close the module (Figure 4). Initially, the subject was positioned facing the Maintenance Task. Upon command, he performed the task according to the following sequence of steps:

1. Open Module

   Fold back hinged cover doors after removing four 3/4-inch hex nuts (with wrench) and flat washers from fixed bolts.

2. Remove Front Door Bolts

   Remove front door holding-bolts by unscrewing two 3/4-inch hex nuts and flat washers.

3. Remove Filter Element Lid

   a. Remove two 3/4-inch hex nuts from holding bolts on split-ring clamp by means of open-end and socket wrenches applied simultaneously.

   b. Pry half of split-ring clamp loose with wrench end and force other half loose with wrench. Remove filter lid and clamp halves and place on access shelf at water filter base.

4. Remove Filter Element

   a. Remove 3/4-inch hex nut from threaded retaining rod and place on access shelf.

   b. Lift filter element out.

5. Replace Filter Element

   Reverse of Step 4.

6. Replace Filter Lid

Reverse of Step 3.

7. Disconnect Water Filter Assembly

a. Remove four 3/4-inch hex nuts and flat washers from connecting bolts on side flange by simultaneous application of open-end and socket wrenches.

b. Remove four 3/4-inch hex nuts and flat washers from threaded studs on base flange with socket wrench.

c. Place bolts, nuts, and washers on access shelf.

8. Move Water Filter Assembly to Storage Area

a. Lift filter off support bracket and base retaining studs.

b. Lower filter (weighing 35 pounds) to storage shelf six inches below support bracket.

9. Move Replacement Filter Assembly to Task Site

Lift filter assembly from storage shelf to task location. (Reverse Step 8B).

10. Install Filter Assembly

a. Place filter assembly on support bracket, align flange holes to retaining studs and slide filter assembly into place.

b. Reverse of Step 7.

c. Tighten each side flange nut to ten foot-pounds loading by means of a sensory torqu wrench.

11. Replace Door Bolts

Reverse of Step 2.

12. Close Module

Reverse of Step 1.

Mental Task

The task consisted of the additional or subtraction of pairs of 3, 4 and 5 digit numbers (numerical reasoning). These computations were performed on one side of an opaque plastic sheet. The subject then turned the sheet over in a manner identical to page turning and entered the obtained answer in a keyed entry form containing an alpha-numerical keying system for each entry blank (digit memory span). The answer was then placed in an alpha-numerically keyed matrix immediately below the keyed entry form in accordance with the coordinates given in the keyed entry forms. See Appendix A for illustration.

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UPON WORK EFFICIENCY OF DIVERS

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13. ABSTRACT

The effects of working underwater upon certain human performance characteristics during the execution of specific complex tasks were studied. The tasks examined were:

1. A complex maintenance task involving the disassembly and reassembly of a water filtration unit,
2. The execution of a mental task involving the processes of numerical reasoning, digit memory span and pattern perception.

These tasks were performed in self-paced fashion at a working depth of 33 feet. During test sessions measures were taken of breathing gas consumption rate, (Liters/min. STPD, air), as well as time and accuracy measures of the task performed. These measurements were then placed in a format which enabled comparison of dependent variable values at ground level and depths of five and thirty three feet.

DD FORM 1 NOV 65 1473

Security Classification

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
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Underwater ergonomics						
Breathing gas consumption						

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ERRATA

Effects of the Underwater Environment
Upon Work Efficiency of Divers

Contract N00014-70-C-0189

Work Unit NR 196-070

September 1970

Certain errata have been detected. These do not affect the conclusions drawn in the report.

Page 3 - Table 1, Maximum Force Production Capabilities in Various Modes:
The column titled Percent Difference in the Linear Mode requires the following change.
Pull - 2 hand reads -12.4; should read -12.7.

Page 5 - Table 3, 3rd column, the heading reads Radius; should read Radius-inches.

Page 7 - Table 4, 1st column, 3rd dependent variable listed, reads Output (ft/lbs/min); should read Output (ft-lbs./min).

Page 8 - Table 5, last column titled:

Ref. #16 66 ft.* Depth	should read	Ref. #16 66 ft. Depth

Page 11 - Table 6, Land Versus Water Comparisons of Time and Heart Rate for the Maintenance Task[14,17]
The Table has the words

Heart Rate (BPM)	Heart Rate (BPM)	Heart Rate (BPM)

over the body of the table. These words should be deleted.

The words Time (seconds) occur over the land, water and difference columns. They should be deleted.

Page 22 - Result section, item 2, 1st line, 5th word, reads "dependent;" should read "independent."

Page 23 - Table 7, Shaffeé 95% Confidence Intervals

Ψ* Productivity as a function of environment (Mental)

reads -11.051 $\leq \Psi_6 \leq$ 5.373;

should read +11.051 $\leq \Psi_6 \leq$ 5.373.